Sensitivity of floodplain geoecology to human impact: A Holocene perspective for the headwaters of the Dijle catchment, central Belgium

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Sensitivity of floodplain geoecology to human impact: A Holocene perspective for the headwaters of the Dijle catchment, central Belgium

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Abstract
Floodplain deposition rates have increased markedly under influence of human impact throughout the late Holocene in many western and central European catchments. Consequently the geomorphology and ecology of many floodplains changed. In this study we discuss this human impact and its influence on the floodplain geoecology during the middle and late Holocene for the headwaters of the Dijle catchment, located in the Belgian loess belt. The floodplain geoecology and the regional vegetation was reconstructed from sedimentological and palynological analyses. An age–depth model for the studied sequences was obtained using 17 radiocarbon dates. Statistical analyses of the pollen data (cluster analysis and canonical correspondence analysis) were used to detect changes in the pollen record. Our data show that until c. 2500 cal. BP, human impact was nearly absent or localized with no discernible influence on the floodplain geoecology. The floodplain was in a stable phase and consisted of a marshy environment where organic material could accumulate, which is interpreted as the natural state of the floodplain. From c. 2500 cal. BP onwards, human impact gradually increased. However, only when human impact in the catchment crossed a threshold around 500 cal. BP, the floodplain geoecology changed with clearing of the Alder carr forest, the establishment of a single channel river and the dominance of minerogenic overbank sedimentation. Spatial variability in the coupling between increasing human impact and changes in floodplain geoecology can be attributed to differences in hillslope–floodplain connectivity and local differences in human impact.

Keywords
floodplain geoecology, Holocene, human impact, pollen analysis, sedimentation rate, statistical analysis

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Introduction

During the early and middle Holocene, most floodplains in the NW European lowlands were rather stable with limited floodplain aggradation resulting in peat formation e.g. in central Belgium (e.g. De Smedt, 1973; Notebaert and Verstraeten, 2010; Notebaert et al., 2009; Vandenberghe and De Smedt, 1979) and in the Paris Basin (e.g. Pastre et al., 2002), or resulting in the development of black floodplain soils in e.g. Germany (e.g. Houben, 2007; Kalis et al., 2003; Rittweger, 2000). During these times floodplains consisted mainly of large marshes where peat accumulated and river channels were absent or small (e.g. De Smedt, 1973; Vandenberghe and De Smedt, 1979). Sediment supply from the slopes to the river valleys increased with increasing human impact through deforestation and the development of agriculture from the Neolithic period onwards (e.g. Notebaert and Verstraeten, 2010). As a result, the floodplain geomorphology and ecology (hereafter called ‘geoecology’) changed (e.g. Houben, 2007; Notebaert and Verstraeten, 2010; Zolitschka et al., 2003). The present-day meandering small river channels in NW Europe are thus the indirect result of anthropogenic activities, i.e. land-use change. Similar changes in floodplain morphology have been demonstrated for the eastern USA, where 19th century human impact through mill dam construction following European colonization is seen as the main trigger (Walter and Merritts, 2008). Although this general framework of changes in river geoecology in relation to the growing impact of humans during the Holocene is now established, many uncertainties on the exact timing and nature of this relation still exist. First, it remains a question whether the floodplain geoecology gradually changed, coinciding with the gradually increasing human impact in the catchment (e.g. Dotterweich, 2008; Kalis et al., 2003), or that changes in floodplain geoecology were abrupt and only occurring when a certain threshold in human impact has been reached (e.g. Houben et al., 2012; Kalicki et al., 2008; Lespez et al., 2008; Notebaert et al., 2011b). Related to this, it is unclear when exactly these changes in river geoecology occurred, and whether these changes occurred simultaneously in the entire catchment. If not, the question remains if these differences in subcatchments can be attributed to the difference in sensitivity towards environmental disturbances, which in turn can indicate a non-linearity in the

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process–response relation. Owing to these uncertainties, it is still a question what exactly the natural state of a floodplain of lowland rivers in NW Europe was, and to which extent human impact has altered the floodplain geoecology (e.g. Brown, 2002; Buijse et al., 2002; Tockner and Stanford, 2002). Such information on the natural reference situation – before significant catchment deforestation and management of floodplain systems (e.g. Brown, 2002) – and the behavior of floodplains under changing human impact is very useful for river management and river restoration (e.g. Newson and Large, 2006; Wohl et al., 2005). Owing to the strong human impact in NW Europe, however, at present no lowland rivers are in a natural state (e.g. Tockner and Stanford, 2002) and therefore the study of past river systems during times that human impact was limited is necessary. In this paper we consider a natural river as a river for which all components are still in a pristine situation, including the non-direct impact e.g. through changes in water or sediment fluxes.

Here, we aim to provide insights into the spatial and temporal relation between human impact and changing floodplain geoecology. We present a detailed reconstruction of the floodplain geoecology for two upland tributary rivers in the Dijle catchment, central Belgium. Information on changes in river geomorphology is gathered through detailed field-based sediment coring. For reconstructing local and regional land use, palynological data were used. Time control is facilitated by radiocarbon dates of crucial lithological and/or palynological transitions.

Material and methods

Study area

This study focuses on the Dijle catchment upstream of Leuven (758 km²), situated in the central Belgian loess belt (Figure 1). The topography of the Dijle catchment exists of an undulating plateau into which several rivers are incised. The geology is dominated by alternating Paleogene sands and clays dipping towards the north, which are covered with Pleistocene loess. In the incised river valleys in the southern part of the catchment, Palaeozoic basement rocks crop out. The soils of the catchment are mainly Luvisols developed in the loess deposits. Locally, loess has been eroded resulting in sandy outcrops. During the first half of the Holocene, the Dijle catchment was mainly forested, as indicated by previous palynological research in the Dijle catchment (e.g. De Smedt, 1973; Mullenders and Gullentops, 1957; Mullenders et al., 1966). The oldest known Neolithic settlement near the Dijle catchment dates from c. 6200 cal. BP (Crombé and Vanmontfort, 2007), first palynological traces of agriculture (e.g. cereal-type grasses) date back to c. 5000 cal. BP (Mullenders et al., 1966), although previous palynological data had a poor chronological control. Anthropogenic disturbances in the landscape became more evident in the pollen assemblages from 2500 cal. BP on, with up to 60% of upland herbs and 10% of cereal-type pollen (Mullenders and Gullentops, 1957; Mullenders et al., 1966), and peaked during the Roman Period (c. 2050–1600 cal. BP) and from the Medieval Period onwards (e.g. Van Hove et al., 2005). At present, land use is dominated by cropland, except for some large deciduous plantation forests in the northeast and northwest of the catchment. The floodplain is currently mainly used as forest or grassland.

For the Dijle river and tributaries, insights into Holocene sediment dynamics is already provided by different studies (e.g. Notebaert et al., 2009, 2011a, 2011b; Rommens et al., 2005, 2006; Verstraeten et al., 2009). A time-differentiated sediment budget constructed for the Dijle catchment by Notebaert et al. (2011b) shed light on the changing sediment dynamics in the catchment. First colluvial deposition is reported from c. 4000 cal. BP and became more important between c. 2000 and 700 cal. BP. The increase in alluvial deposition in the Dijle catchment occurred later than the increase in colluvial deposition, with the major part of floodplain sedimentation since c. 1000 cal. BP. The increasing colluvial and alluvial deposition coincided with the increasing intensity in agricultural activities in the catchment, whereas little evidence exists for the influence of climate variability on the colluvial and alluvial deposition pattern (Notebaert et al., 2011b).

In this study, we consider the headwaters of the Dijle catchment, where a strong connection between sediment sources (i.e. hillslopes and loess plateau) and floodplains is expected. Two study sites in the headwaters are selected, one near the village of Sclage along the Cala River, and one near the village of Cortil along the Orne River (Figure 1). Both rivers are tributaries of the main Dijle River. The upstream area of both sites is c. 13 km². The width of the floodplain in Sclage is c. 90 m compared with c. 70 m in Cortil. These sites were selected based on their accessibility, availability of previous research and mainly on their differences in slope morphology and land cover history. The difference in slope morphology is related to differences in geology. The Cala River has cut through the sandy Tertiary deposits, resulting in outcrops of more resistant Palaeozoic rocks. Consequently, the slopes along the axes of the Cala River are steeper (up to 40%) comparing with slopes along the Orne River (less than 5%), which has not cut through the sandy Tertiary deposits. The Cala floodplain at Sclage is consequently surrounded by steep slopes, whereas the Orne floodplain at Cortil is more open (Figure 1). The southwestern part of the Dijle catchment (where the site of Sclage is located) lacks archaeological findings from the Roman Period, whereas in the surroundings of the site of Cortil a cluster of Roman findings can be identified (Figure 1) (Notebaert, 2009), indicating a difference in land cover history between both sites.

Coring and sediment analysis

Information for the reconstruction of the floodplain morphology is retrieved from coring data, grouped in transects across the floodplain, one at both study sites. The coring transect at Sclage contains 11 cores with a coring spacing of 5–15 m. At Cortil five cores were made with a spacing of 10–20 m. For each coring, a detailed sedimentologic field description was made with a vertical resolution of 5 cm, containing texture and sorting determined by palpation, colour description, and determining inclusions (such as gravel, plant material and artefacts). For each study site, one sediment core along the transect was collected for pollen analyses (Figure 2). The main focus of this study is the change in floodplain geoecology, especially the transition from peaty deposits towards minerogenic overbank deposits. Therefore the location of the pollen profiles on the transect was chosen based on a good preservation of this transition (e.g. no indications of erosion of the peat). For the same reason a specific depth range was selected around this transition in which pollen analyses and additional lab analyses were performed: for Sclage between 285 and 415 cm (Figure 2) and for Cortil between 215 and 370 cm depth (Figure 2). Thermogravimetric analysis (loss on ignition, LOI), using the methods of Konert and Beets (unpublished data, 2012), was performed to determine organic matter (OM) and carbonate content. Based on the analysis of the sediments, and taking into account the homologous contemporary deposition in the floodplain, the sediments are grouped in different facies representing different depositional environments, similar to Notebaert et al. (2011a).

Palynological analysis

For each study site a palynological analysis was performed for the selected depth range (Figure 2). Pollen samples were taken at a vertical resolution of c. 4 cm around the transition from peaty

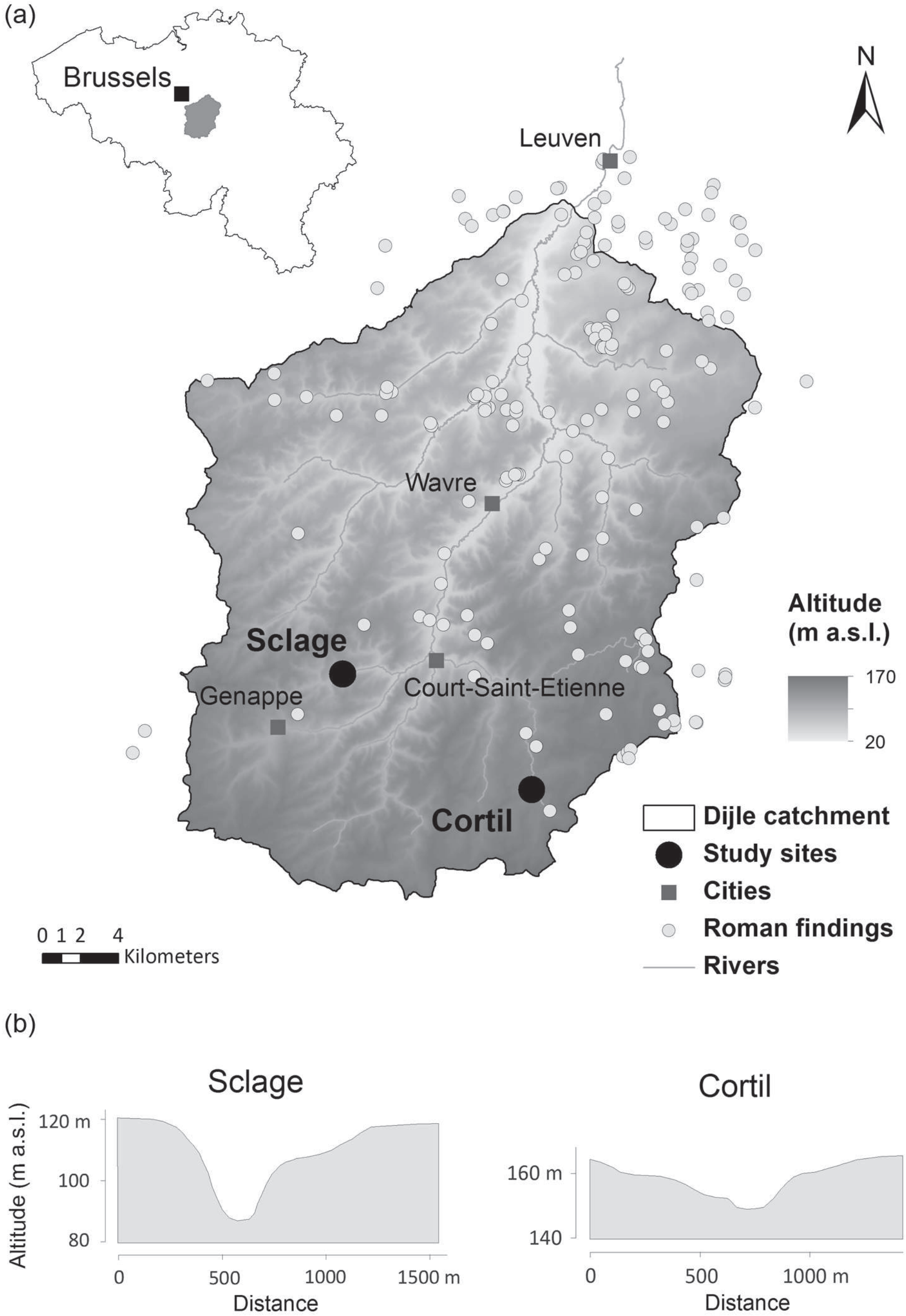

Figure 1. (a) Location of the study sites Sclage and Cortil in the Dijle catchment and in Belgium, with indications of Roman findings in and near the Dijle catchment (location of archeological findings based on Notebaert (2009)); (b) cross-section from the loess plateau towards the floodplain for both study sites.

deposits towards minerogenic deposits, and a vertical resolution of c. 8 cm when no changes in sediment were observed. Pollen samples were extracted from the core using a sampler of defined volume (100 mm³ for organic rich sediment, 200 mm³ for minerogenic sediments), and were prepared following the standard technique of Faegri and Iversen (1989). A known quantity of *Lycopodium* spores was added, to allow the calculation of pollen accumulation rates (PAR) and charcoal accumulation rates (CHAR). The samples were studied under a 630× and 1000× magnification using oil immersion. Pollen types were identified using Moore et al. (1991), Beug (2004) and a modern reference collection; non-pollen palynomorphs by using Van Geel (1978). Pollen data are expressed as relative frequencies (percentages) of the pollen sum. The pollen sum includes the regional pollen signal, including upland herbs, Poaceae, trees and shrubs. Wetland vegetation (e.g. *Alnus, Salix*, Cyperaceae and Typhaceae) is interpreted as local vegetation and is left out of the pollen sum, as well as the aquatic species. Percentage diagrams were divided into regional and local components and constructed using *C2* computer program (Juggins, 2007). Pollen slide charcoal particles (50–200 μm) were counted and charcoal accumulation rates (CHAR, particles/cm^2 per yr) were calculated by taking into account the floodplain accumulation rate. Likewise, pollen accumulation rates (PAR, pollen/cm^2 per yr) were also calculated.

C^{14} analysis and floodplain accumulation rates

AMS radiocarbon dating of organic material embedded in organic or floodplain deposits was used to provide a chronostratigraphical framework for the pollen assemblages (Table 1). After

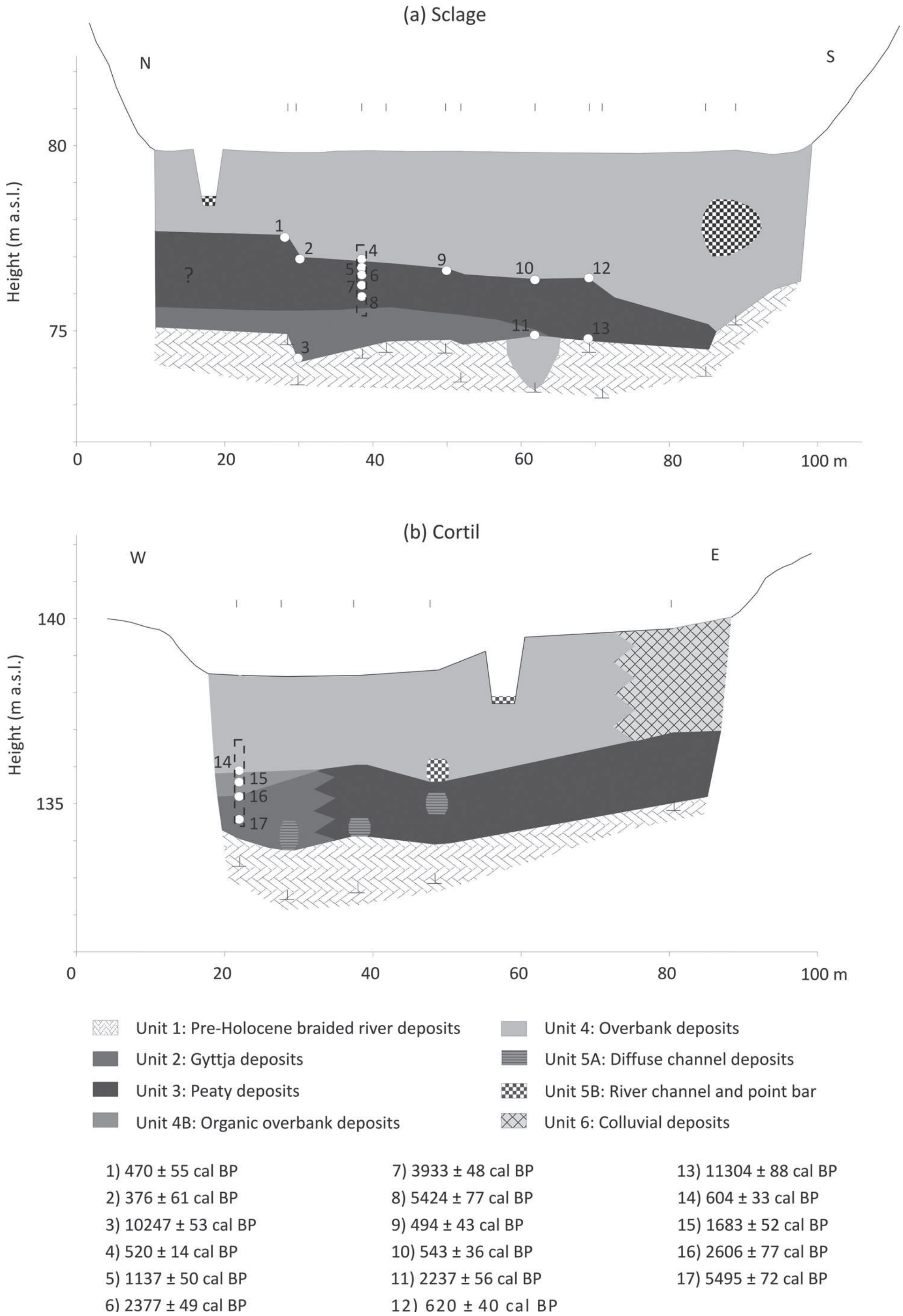

Figure 2. Cross-section of (a) the Cala floodplain near Sclage and (b) the Orne floodplain near Cortil (location, see Figure 1), with indication of the different lithogenetic units. Dotted rectangular indicates location of pollen profile, vertical lines indicate location and bottom of the individual corings.

sieving samples at 250 mm, terrestrial plant remains were hand-picked, and identified for dating. Obtained ages were calibrated using the IntCal09 calibration curve (Reimer et al., 2009) and *Oxcal 4.1* software (Ramsey, 2009). An age–depth model was established for each site based on the *clam.R* package (Blaauw, 2010) using linear interpolation between the dated levels. Based on the age–depth model, a timescale for the whole sequence was derived for each site. The age–depth model was used to estimate the dates of each transition in both the pollen diagram and floodplain architecture. Dating results were used to calculate floodplain accumulation rates (mm/yr). Post-depositional compaction of peat and peaty deposits can lead to an underestimation of the peat growth rate and consequently to an underestimation of floodplain accumulation rates. Therefore the porosity–depth equation, developed by Sheldon and Retallack (2001) for non-marine sediments, was used to estimate compaction of the peat deposits:

$$C = -S_i / [(F_0/e^{Dk}) - 1] \quad (1)$$

where C is the compaction as a fraction of the original thickness, S_i is the initial solidity, F_0 is the initial porosity, D is the burial depth and k is an empirically derived constant. Following Sheldon and Retallack (2001), $S_i = 0.06$, $F_0 = 0.94$ and $k = 2.09$ were used to incorporate peat compaction. Using these values, and assuming that the difference in peat compaction for peat layers with a LOI

Table 1. Radiocarbon dating results.

No.	Sample ID	Lab code	Conventional age (BP)	Calibrated radiocarbon age (cal. BP) ± 1σ error	Location	Depth (cm)	Dated material	Stratigraphic position
1	SCL 4-2	Beta-257424	430 ± 40	470 ± 55	Sclage	230	wood remains	top peat layer
2	NB-SCL-50-9	Beta-297818	300 ± 40	376 ± 61	Sclage	270	wood remains	top peat layer
3	NB-SCL-50-17	Beta-297819	9080 ± 50	10,247 ± 53	Sclage	515	wood remains	bottom gyttja layer
4	NB-SCL102-D1	Beta-302449	480 ± 30	520 ± 14	Sclage	304	wood remains	top peat layer
5	SCL-102-4-D5	Beta308870	1210 ± 30	1137 ± 50	Sclage	319	terrestrial plant remains	peat layer
6	NB-SCL102-D9	Beta-302450	2350 ± 30	2377 ± 49	Sclage	339	terrestrial plant remains	peat layer
7	SCL-102-4-15	Beta-308869	3620 ± 30	3933 ± 48	Sclage	371	terrestrial plant remains	peat layer
8	NB-SCL102-D12	Beta-302451	4700 ± 30	5424 ± 77	Sclage	399	terrestrial plant remains	peat layer
9	SCL 3-2	Beta250211	450 ± 40	494 ± 43	Sclage	330	wood remains	top peat layer
10	NB-SCL-53-9	Beta-297820	510 ± 40	543 ± 36	Sclage	340	wood remains	top peat layer
11	NB-SCL-53-17	Beta-297821	2230 ± 40	2237 ± 56	Sclage	490	terrestrial plant remains	bottom gyttja layer
12	SCL 2-1	Beta2577361	670 ± 40	620 ± 40	Sclage	320	terrestrial plant remains	top peat layer
13	SCL 2-7	Beta-257243	9870 ± 60	11,304 ± 88	Sclage	500	wood remains	bottom peat layer
14	COR-103-D4	Beta-308864	620 ± 30	604 ± 33	Cortil	245	terrestrial plant remains	floodplain fines
15	COR-D12	Beta-323481	1770 ± 30	1683 ± 52	Cortil	269	plant remains	floodplain fines
16	COR-103-D1	Beta-308862	2520 ± 30	2606 ± 77	Cortil	320	wood remains	top gyttja layer
17	COR-103-D3	Beta-308863	4760 ± 40	5495 ± 72	Cortil	370	terrestrial plant remains	gyttja layer

ranging between 40% and 60% is negligible, the compaction ratio (C) becomes e.g. 0.91 at 3 m and 0.85 at 5 m depth (91% and 85%, respectively, of the original thickness), which is used to make realistic estimates of floodplain accumulation rates.

Statistical analysis

In order to provide more objective insights into the pollen data, each pollen record was divided into different zones using a quantitative approach: samples are grouped by applying a hierarchical cluster analysis. A cluster analysis was performed for each study site and for both the regional and local pollen signal separately. The used clustering method is 'average linkage clustering', where the distance between two clusters is defined as the average of all possible distances between members of the two clusters. As a distance measure, one minus the cosine of the included angle between points has been used, as it is assumed that this provides the best results for ecological data (Hammer and Harper, 2006). The resulting cluster tree was firstly split into a set of larger groups (indicated with numbers), and secondly subdivided into smaller clusters (indicated with letters). In this way, the hierarchy of the clusters was preserved.

Canonical correspondence analysis (CCA) was performed to gain more insights into the changes in the pollen record through time. Correspondence analysis (CA) is a mathematical tool for detecting structures, trends and gradients in large data sets. It displays high-dimensional data in a lower-dimensional space (such as the two-dimensional plane), while maintaining most of the original information. It has previously been applied to pollen data (e.g. Birks, 1985; Birks et al., 1988; Kerig and Lechterbeck, 2004; Lechterbeck et al., 2009). Full explanation of CA is provided by Shennan (1997) and Hammer and Harper (2006). In canonical correspondence analysis, an independent variable is set to optimize the result so that variation correlates with the independent variable. Here we used the chronology as the independent variable such that the result is optimized to changes in the pollen record through time, which is an advantage compared with CA or principal component analysis (Ter Braak, 1986). Plotting the scores on the first CCA axis as a function of time has previously been used as an indicator for human impact (e.g. Kerig and Lechterbeck, 2004; Lechterbeck et al., 2009). By analysing pollen data from different sites in one single step, the results can be directly compared over the sites (Lechterbeck et al., 2009). In this study, a CCA was applied on the regional pollen data of both study sites. Rare taxa were excluded from the CCA as these can cause statistical problems. Here rare taxa were defined as taxa that occurred in less than 7% of the samples.

Results

Floodplain architecture

Different sedimentary facies were identified in both sites (Table 2). Similar facies were found by Notebaert et al. (2011a) in the Dijle catchment. Cross-sections of the floodplain in study site Sclage and Cortil are shown in Figure 2. Facies unit 1 consists of compact silty to loamy sediments with a low OM content, deposited at the base of the cross-sections. This unit is interpreted as Weichselian Lateglacial river deposits, or in situ loess deposits (Notebaert et al., 2011a). Facies unit 2 are gyttja deposits: very organic sediments (LOI values above 40%) deposited in open water environments such as small ponds. Facies unit 3 is a peaty layer, containing mostly reed peat or woody peat (LOI values above 40%). Units 2 and 3 are overlain by silty to clayey overbank deposits with low OM content (LOI values below 10%) (unit 4). At some places unit 4 has slightly higher OM content (LOI values of c. 15%), which is indicated as unit 4B. The transition between the peaty and gyttja deposits (unit 2 and 3), and the overbank deposits (unit 4) is abrupt but not erosive. Facies unit 5A consists of alternations of strong organic silty to clayey deposits and fine sandy layers, interpreted as multichannel deposits. Facies unit 5B consists of

Table 2. Lithogenetic units identified in both study sites. Same units were found by Notebaert et al. (2011a) for the whole Dijle catchment.

Unit	Texture	Position	Interpreted deposition environment	Age
1	Compact silty to loamy sediments	Bottom of the floodplain deposits	Braided river deposits	Pre-Holocene
2	Gyttja deposits	Above unit 1, covered by unit 3 or 4	Open water deposits	From early Holocene to c. 2500 cal. BP, depending on location
3	Peat to very organic silt and clays	Above unit 1 and 2, covered by unit 4	Marshy floodplain	From early Holocene to c. 500 cal. BP, depending on location
4	Silty clay loam to loam	Top of floodplain	Overbank deposits	From c. 600 cal. BP, depending on location
4B	Silty clay loam to silt loam, contains some organic material	Above unit 2, covered by unit 4	Overbank deposits	From c. 2500 to 600 cal. BP
5A	Alterations of organic silty clay loam and fine sand deposits	Included in unit 2 and 3	Small diffuse channel deposits	From early Holocene to c. 500 cal. BP, depending on location
5	Sandy loam and sands	Above unit 2, 3 and 4; sometimes included in unit 4	River channels and point bar deposits	After c. 2500 cal. BP
6	Silty clay loam to sandy deposits, arranged in layers	At location of colluvial fans	Colluvial deposits	After c. 2500 cal. BP

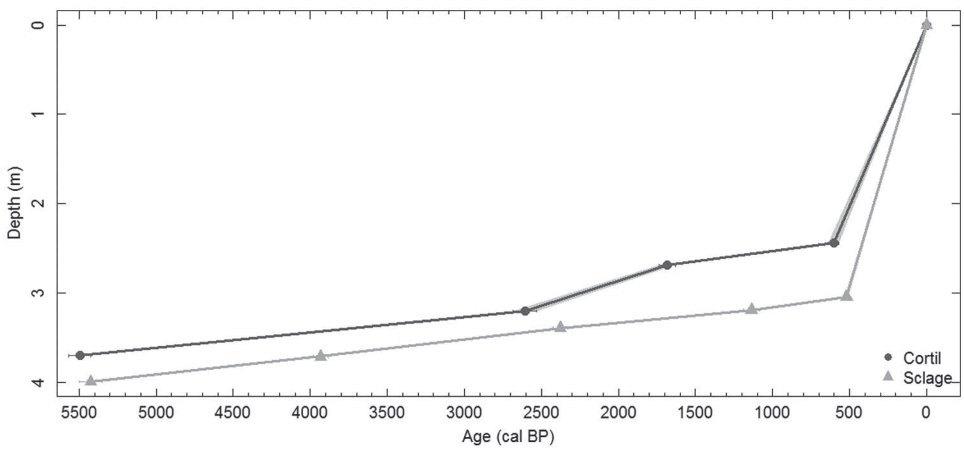

Figure 3. Calibrated AMS ^{14}C dating results and floodplain accumulation for the two study sites Sclage and Cortil.

sandy sediments, without intermediate finer layers, and is interpreted as channel and point bar deposits because of their position and texture. Finally, facies unit 6 consists of silty clay loam to sandy deposits, arranged in layers and often containing brick fragments and is interpreted as a colluvial deposit. This unit covers unit 3, indicating that unit 6 is deposited after the formation of these organic-rich layers.

The base of units 2 and 3 is dated at c. 10 ka cal. BP (Table 1). The top of the peaty deposits (unit 3) is slightly diachronic in Sclage, ranging between 376 ± 61 cal. BP and 620 ± 40 cal. BP. In Cortil, the top of unit 2 is dated at 2606 ± 72 cal. BP; the top of unit 4B at 604 ± 33 cal. BP. After around 400 cal. BP in Sclage and 600 cal. BP in Cortil, the entire floodplain is dominated by minerogenic overbank deposits with low OM content (unit 4). Based on the dating results (Table 1), an age–depth model was made for both sites (Figure 3). Results are rather similar for both sites. Floodplain accumulation rates are constant at c. 0.2 mm/yr until c. 1650 cal. BP. This constant rate continues at Sclage until c. 520 cal. BP, while floodplain accumulation increases to c. 0.6 mm/yr for Cortil. From c. 520 cal. BP onwards, sediment accumulation rates increased up to 6 mm/yr at Sclage, and from c. 604 cal. BP onwards it increases to 4 mm/yr at Cortil. For both sites, this increase coincides with the transition from the organic floodplain deposits (unit 2 and 3) to the minerogenic floodplain deposits with very low OM content (unit 4).

Local and regional vegetation

The regional pollen signal for the site of Sclage (Figure 4) can be split up in two major clusters (Figures 4 and 5). Cluster 1 (415–345 cm) contains high values of arboreal pollen (AP) (especially high values of *Corylus* and *Tilia*) and low values of non-arboreal pollen (NAP – containing Poaceae and upland herbs). Cluster 2 (345–286 cm) can be split in two subclusters. Cluster 2A (345–303 cm) contains decreasing values of AP (decreasing values of *Corylus* and *Tilia*, but increasing values of *Quercus* and *Fagus*) and increasing values of NAP and anthropogenic indicators (e.g. cereal-type and *Plantago lanceolata*). Cluster 2B (303–286 cm) contains low values of AP and high values of NAP, including Poaceae and other anthropogenic indicators. CHAR and floodplain accumulation rates are increasing from the beginning of cluster 2B upwards (Figure 4).

The cluster analysis of the local pollen signal of Sclage results in two major clusters (Figures 4 and 5). Cluster 1 (415–300 cm) is characterized by the absence of Typhaceae and low (cluster 1A, 415–400 cm) to high (cluster 1B, 400–300 cm) values of *Alnus*. Cluster 2 (300–286 cm) contains especially high values of Typhaceae.

The pollen diagram of the site Cortil is shown in Figure 4. The regional pollen signal can be divided in two major clusters (Figures 4 and 5). Cluster 1 (373–305 cm) contains mainly high AP values and low NAP values. This cluster can be split in Cluster

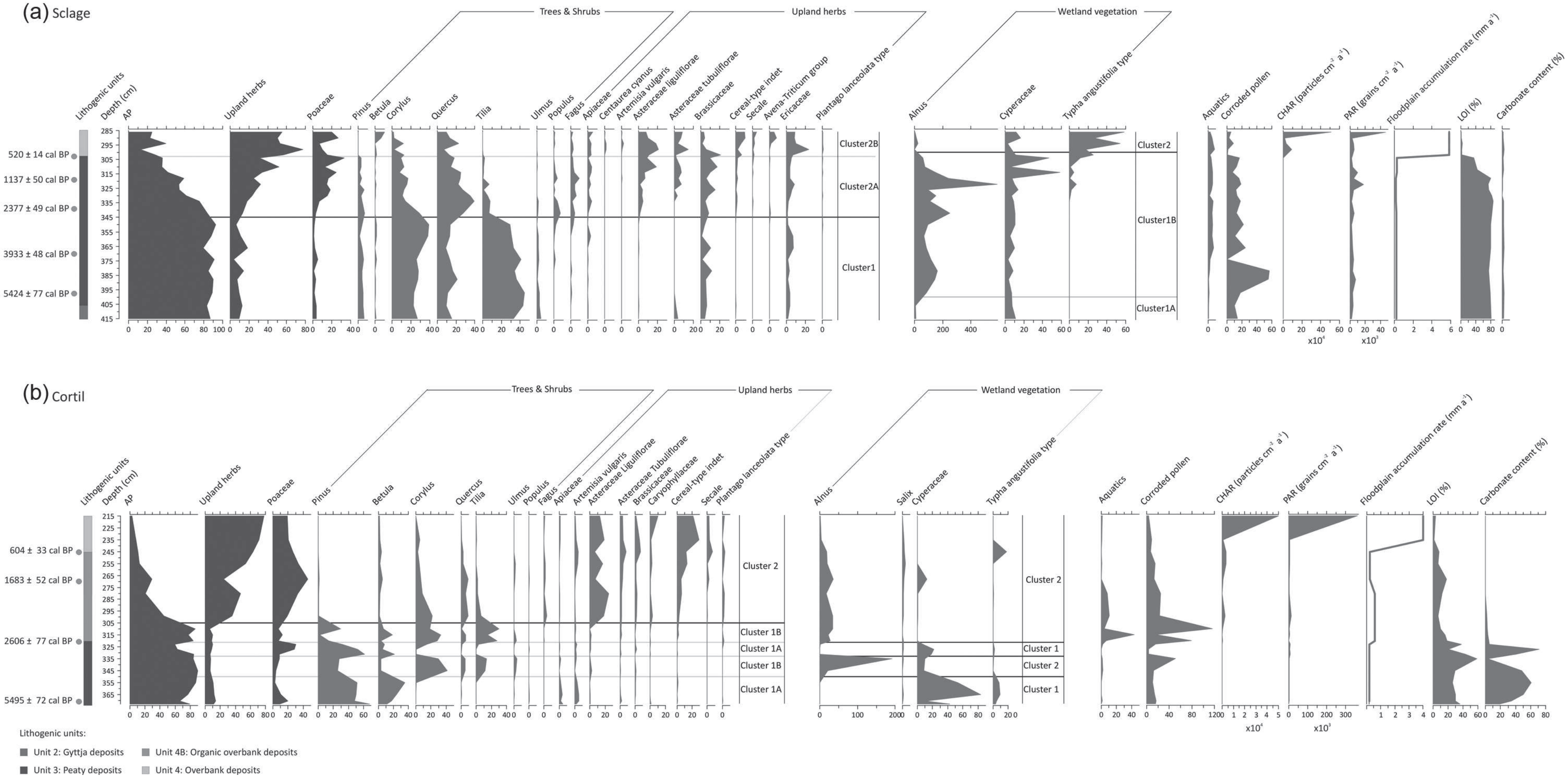

Figure 4. Simplified pollen diagram from site (a) Sclage and (b) Cortil; with indications of the different clusters.

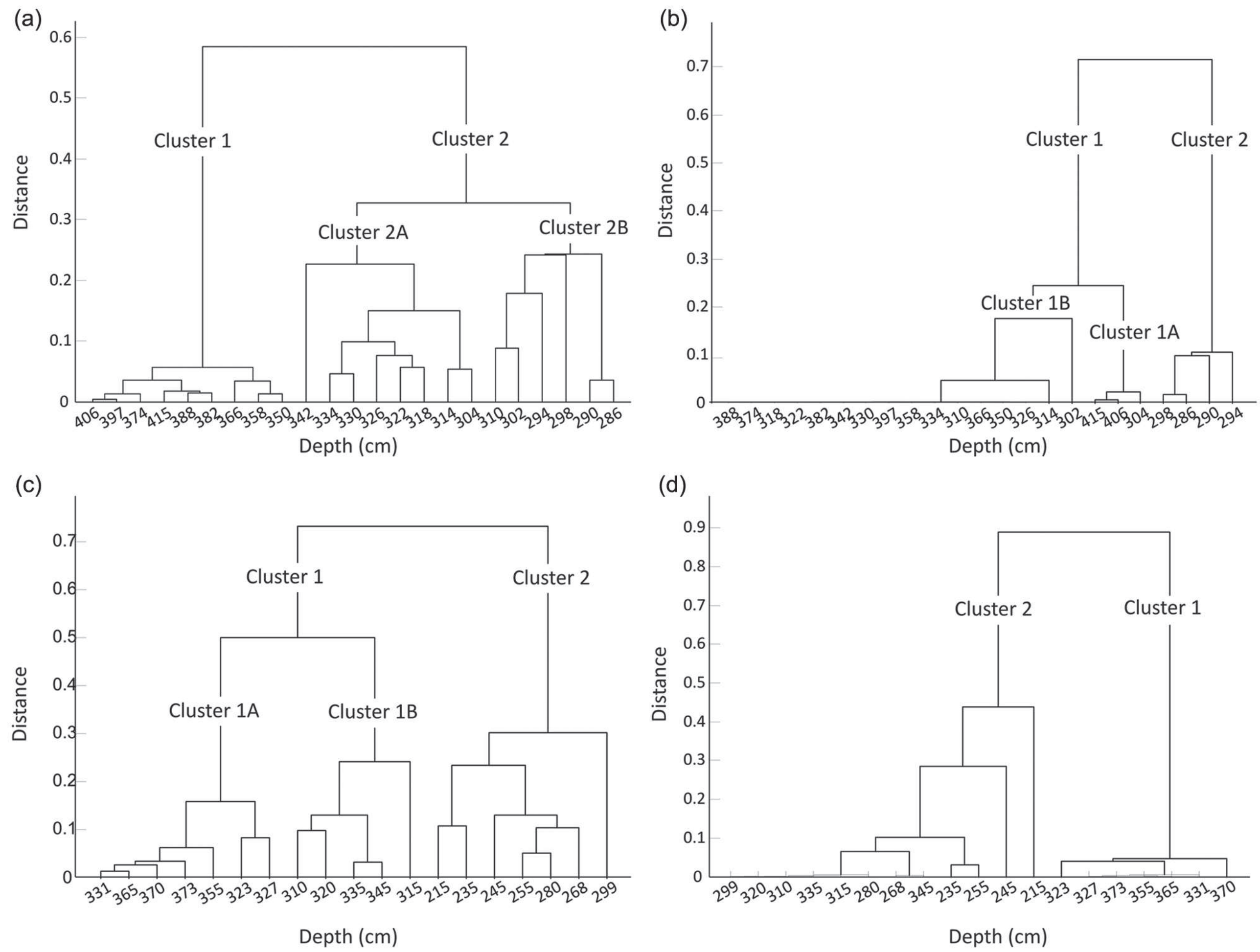

Figure 5. Clustering tree for (a) the regional pollen signal at Sclage; (b) the local pollen signal at Sclage; (c) the regional pollen signal at Cortil; (d) the local pollen signal at Cortil. The height of each branching point represents the distance between the two objects being connected.

1A containing very high values of *Pinus* (up to 60%), and Cluster 1B containing high values of *Tilia* and *Corylus* and low values of *Pinus*. Cluster 2 (305–215 cm) contains low AP values and high NAP values including high values of Poaceae and anthropogenic indicators. CHAR and floodplain accumulation rates are increasing from 320 cm and are further increasing from 240 cm onwards.

The local pollen signal of Cortil can be divided in two major clusters (Figures 4 and 5). Cluster 1 contains high values of Cyperaceae, and low values of *Alnus*. This cluster coincides with cluster 1A of the regional signal. Cluster 2 contains mainly high values of *Alnus*, while Cyperaceae are almost absent. This cluster coincides with cluster 1B and cluster 2 of the regional signal.

Semi-quantification of human impact

The results of the CCA (Figure 6) for both sites show that forest taxa have low scores on the first CCA axis, whereas cultural indicators and all taxa associated with arable fields have high scores. Therefore, the scores on the first CCA axis can be seen as an indicator for human impact. However, the scores are dimensionless and it is not possible to couple them with absolute numbers of settlements or area under human impact (e.g. Lechterbeck et al., 2009). When plotting the scores on the first CCA axis as a function of time (Figure 6), an increase in human impact is suggested for both study sites. From c. 6000 cal. BP until 2500 cal. BP human impact is at its lowest level in both sites. Within this time span there is a small variation in human impact for Cortil, which can however not directly be linked with the alternation between cluster 1A and 1B (Figure 6). However, the significant increase in human impact starts more or less at the same time for both sites: around 2670 cal. BP at Sclage and 2340 cal. BP at Cortil. The increase in human impact in Sclage is rather gradual and reaches its highest level around 520 cal. BP. For Cortil, human impact increases to high levels in a shorter period (between c. 2340 cal. BP and 2000 cal. BP), and reaches the highest level around 600 cal. BP.

Discussion

Reconstruction of the floodplain geoecology

Sclage. Our data illustrate that from the beginning of the Holocene onwards the floodplain was a strongly vegetated and stable environment – i.e. an environment with limited sediment discharge and sediment deposition – resulting in peat and gyttja accumulation. Palynological data, used for the reconstruction of the floodplain ecology, were obtained for the period between c. 6100 cal. BP and 520 cal. BP. The ecological reconstruction shows that from c. 6100 cal. BP until 5460 cal. BP the floodplain was an open water system, resulting in gyttja deposits (Figures 2 and 4). These open water conditions are thought to be shallow lakes related to groundwater seepage in the floodplain. The sedimentological data shows limited sediment deposition (Figure 3), floodplain accumulation rates are of the order of 0.2 mm/year.

From c. 5460 cal. BP until 520 cal. BP, the floodplain was dominated by Alder carr forests (*Alnion glutinosae*) (Figure 4). At this stage, no clear river channel was present in

(a)

Pollen type	score on 1st CCA axis	Ecotype	Cultural indicator
Pinus	-0.79425	Forest	
Tilia	-0.75771	Forest	
Ulmus	-0.6406	Forest	
Betula	-0.50766	Forest	
Corylus	-0.25983	Forest	
Artemisia vulgaris	-0.20902	Ruderal	CI
Acer	-0.08458	Forest	
Quercus	0.2011	Forest	
Apiaceae	0.22809	indiff	
Populus	0.26971	Forest	
Brassicaceae	0.34551	indiff	CI
Fraxinus	0.37384	Forest	
Poaceae	0.42184	Grassland	
Ericaceae	0.54698	Heath	
Plantago lanceolata	0.61195	Grassland	CI
Fagus	0.62814	Forest	
Caryophyllaceae	0.67501	indiff	
Asteraceae tubuliflorae	0.73247	indiff	
Asteraceae liguliflorae	0.83697	indiff	
Chenopodiaceae	0.95456	Ruderal	CI
Cerealia indet	0.96397	Arable fields	CI
Anthoceros	1.06	Arable fields	CI
Secale	1.07113	Arable fields	CI
Avena-Triticum group	1.14634	Arable fields	CI
Centaurea cyanus	1.15925	Arable fields	CI
Plantago major-media group	1.20022	Ruderal	CI

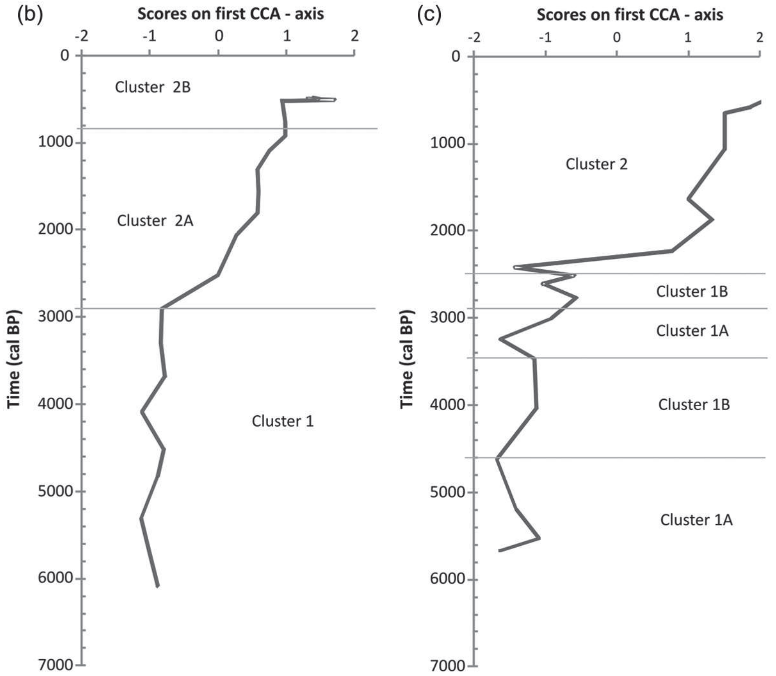

Figure 6. (a) Scores on the first CCA axis for pollen types of both study sites Sclage and Cortil. Scores on the first CCA axis plotted against time for (b) Sclage and (c) Cortil.

the floodplain. Instead the floodplain consisted of a marshy environment probably with a diffuse river pattern, as indicated by the limited sediment accumulation and the absence of channel deposits from this period (Figure 2). The *Alnion glutinosae* resulted in peat accumulation in the floodplain with an average peat accumulation rate of c. 0.2 mm/yr.

Around 520 cal. BP, the *Alnion glutinosae* disappeared and was replaced by an open floodplain dominated by Cyperaceae, Poaceae and Typhaceae (Figure 4). This transition occurred in a very short period (< 250 yr), and is probably related to clearing of the *Alnus* forest and reclamation of the floodplain into wet meadows. At this transition, the sediment deposition increased from c. 0.2 mm/yr to c. 6 mm/yr. Consequently the peat accumulation stopped and was replaced by minerogenic overbank deposits. The top of the peat layer is slightly diachronic over the cross-section, ranging between 620 ± 40 cal. BP and 376 ± 61 cal. BP (Figure 2). We suggest that the diachronic transition between the two lithogenic units is due to the gradual build-up of levees that laterally expanded over the backswamp areas when the sediment input increased. The build-up of the levees started at the southern side of the valley as suggested by the older dates, the lower elevation of the top of the peat and an old river channel at this side of the valley (Figure 2). After c. 376 cal. BP, the entire floodplain was dominated by minerogenic sediment deposition, and had an open vegetation. This open floodplain vegetation is also visible on the illustrative *de Ferraris* map (c. 1775, scale 1:11,520), and in the present floodplain.

Cortil. Also at Cortil the floodplain was vegetated and relatively stable with limited sediment deposition from the beginning of the Holocene onwards, resulting in peat and gyttja accumulation. Facies unit 5A indicates that small diffuse channels were present in the floodplain during the formation of these peat and gyttja deposits. The reconstruction of the floodplain ecology goes back to c. 5495 cal. BP. Between c. 5495 cal. BP and 2670 cal. BP, the vegetation in the floodplain shows an alternation between an open floodplain, dominated by Cyperaceae, Poaceae, Typhaceae and *Salix* on the one hand, and *Alnion glutinosae* on the other hand (Figure 4). This alternation is interpreted to be related to changes in wetter and dryer conditions in the floodplain, illustrated by the changing $CaCO_3$ content (Figure 4) due to changing input of calcareous rich groundwater seepage. During drier stages the floodplain is dominated by *Alnion glutinosae*; while during wetter stages the floodplain is more open and dominated by Cyperaceae, Poaceae and Typhaceae. During these alternations however, there is a constant low sediment deposition in the floodplain, resulting in organic (peaty and gyttja) deposits with an average floodplain accumulation rate of 0.2 mm/yr (Figure 4).

From 2670 cal. BP to 620 cal. BP, the floodplain is dominated by *Alnion glutinosae*. Sediment accumulation is increasing, resulting in a cessation of peat accumulation. Instead, moderately organic (LOI values of c. 10%) overbank deposits are found in the floodplain, with a sediment accumulation rate of 0.4 mm/yr (Figure 4). This transition is rather gradual.

From 620 cal. BP onwards, the *Alnion glutinosae* disappears and is replaced by wet meadows. This is also the land use type which is indicated on the illustrative *de Ferraris* map (c. 1775). Sediment accumulation increases further to c. 4 mm/yr, and minerogenic overbank deposits with a low organic content (LOI values < 10%) are deposited (Figure 4).

The role of humans in changing the floodplain geoecology

Our reconstruction of the catchment vegetation and the human impact in the catchment dates back from c. 6000 cal BP. From c. 6000 to 2500 cal. BP, the headwaters of the Dijle catchment were covered by deciduous forest, dominated by *Corylus, Tilia* and *Quercus* (Figure 7). Also Mullenders and Gullentops (1957), Mullenders et al. (1966) and De Smedt (1973) reported a deciduous forest in the Dijle catchment for this period. Anthropogenic indicators (e.g. cereal-type and *Plantago lanceolata*) are present in low quantities in the pollen diagrams, resulting in low scores on the first CCA axis (Figure 6). This indicates that human impact was limited or only affecting geomorphology and ecology at a small scale. Consequently, in this period the investigated floodplains consist of a marshy environment with a multichannel river pattern. The floodplain was dominated by an *Alnion*

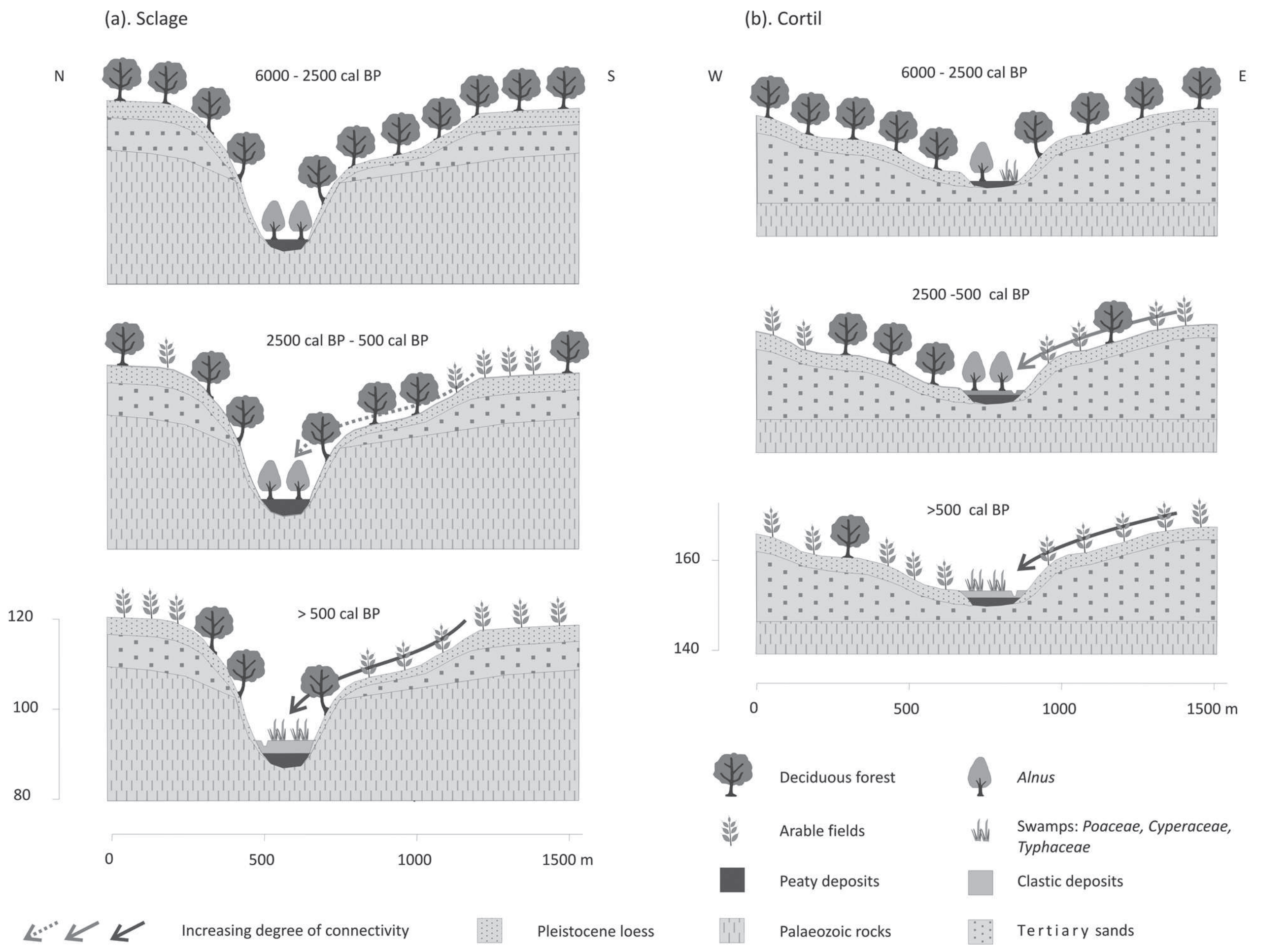

Figure 7. Schematic reconstruction of the floodplain and upland vegetation, for (a) Sclage and (b) Cortil.

glutinosae (Sclage); or characterised by an alternation between an open floodplain environment (dominated by Cyperaceae, Poaceae and Typhaceae) and an *Alnion glutinosae* (Cortil). This marshy environment with diffuse water transport seems to be the natural state of the floodplains of the headwaters of the Dijle catchment, which is also stated further downstream in the Dijle-Demer confluence area by De Smedt (1973) and Vandenberghe and De Smedt (1979).

The *Pinus* pollen present in both diagrams are interpreted as a regional signal of a wider range. We suggest that the *Pinus* trees grew on the nutrient-poor sandy deposits, which can be found north of the Belgian loess belt (De Smedt, 1973) and locally in the Dijle catchment where Paleogene sandy outcrops occur. The higher percentages for Cortil are explained by a better pollen-trapping capacity for *Pinus* at this site because of more open water environments (gyttja deposition) and more gentle valley slopes. A poor trapping capacity at Sclage, because of the continuous dominance of *Alnus* in the floodplain and the forested steep slopes surrounding the floodplain of Sclage, resulted in low pollen values of *Pinus*. Moreover, in the pollen diagram of Cortil (Figure 4), an alternation between high pollen values of *Pinus, Betula* and Poaceae (cluster 1A) on the one hand and *Corylus, Ulmus, Tilia* and *Quercus* (cluster 1B) on the other hand is present. It is suggested that these variations are caused by human-induced forest clearance during cluster 1A and forest regrowth during cluster 1B. However, cluster 1A has no significant higher scores on the first CCA axis (Figure 6), suggesting that these clearances occurred only at a small scale and suggesting a limited coupling between these forest clearances and the floodplain. Nevertheless, we suggest that these alternations in forest clearance and regrowth can be related with the observed alternation in wetter and drier conditions in the floodplain at Cortil (section 'Reconstruction of the floodplain geoecology', subsection 'Cortil'), as the early deforestation could cause increased infiltration on the slopes and seepage in the river valley and consequently caused wet conditions in the floodplain.

From c. 2500 cal. BP onwards, both pollen diagrams reflect a clear increase in human impact (Figure 6). The AP fraction in the pollen diagrams decrease and more upland herbs, Poaceae and anthropogenic indicators appear (Figure 7). This happens earlier in Sclage (c. 2670 cal. BP) compared with Cortil (c. 2340 cal. BP). Also at other sites in the Dijle catchment, the presence of anthropogenic pollen indicators become significant around this time (Mullenders et al., 1966). Simultaneously with this decrease in forest cover, there is a change in the forest composition: whereas previously the forest was dominated by *Tilia* and *Corylus*, now *Quercus* becomes most dominant and *Fagus* appears (Figure 4). Previous research linked this *Tilia* decline with anthropogenic impact (e.g. Bradshaw, 2008; Turner, 1962). Also the slight increase in charcoal accumulation rate illustrates the increasing human impact in the catchment. This first significant increase in human impact in the catchment (around 2670 cal. BP) did not alter the floodplain morphology in Sclage, probably because of the limited connectivity between the cultivated areas and the fluvial system caused by the forested slopes and riparian vegetation surrounding the floodplains (e.g. Houben et al., 2012; Tabacchi et al., 1998) (Figure 7). The floodplain remained a marshy environment dominated by an *Alnion Glutinosae*, with a diffuse drainage network. In Cortil on the other hand, this increased human impact caused a small increase in sediment deposition in the floodplain, suggesting a better coupling between cultivated areas and floodplains as more and more cultivated areas are directly connected with the fluvial system (Figure 7). This resulted in a cessation of the peat accumulation and the start of the deposition of moderately organic minerogenic floodplain sediments.

During the Roman and Medieval periods (from c. 2000 cal. BP until 500 cal. BP) human impact continuously increases, indicated by a further decrease in forest cover and increase in Poaceae, upland herbs and anthropogenic indicators (Figure 7). Human impact appears to be higher in Cortil than in Sclage, as is illustrated by the higher scores on the first CCA axis (Figure 6), which is in agreement with the higher concentrations of archaeological findings from the Roman Period in the surroundings of Cortil (Figure 1) (Notebaert, 2009). This continuous increase in human impact is only interrupted by a small increase in forest cover at Cortil around 1600 cal. BP, which can possibly be coupled with a decreased population density and human impact in Europe during the Migration Period (c. 1750–1600 cal. BP) (Buntgen et al., 2011). From c. 600 cal. BP (Cortil) and c. 520 cal. BP (Sclage) onwards, human impact is at its highest level. This further increase in human impact from the Roman Period onwards resulted in increased overland flow, soil erosion, and colluvial sediment deposition (unit 6 in Figure 2) (Notebaert et al., 2011b). Furthermore, there is a strong increase in floodplain accumulation rate (from c. 0.2 mm/yr to more than 4 mm/yr). Similar trends in accumulation rate were found by Notebaert et al. (2011b) for other sites in the Dijle catchment. This increased sediment input in the river valley and formation of natural levees altered the river morphology towards a single channel river. Consequently, the peat formation in the floodplain stopped, and the floodplain became dominated by minerogenic overbank deposits. Similar trends in floodplain accumulation rates and changes in river morphology are reported in other areas in NW Europe (e.g. Chiverrell et al., 2009; Foulds and Macklin, 2006; Houben, 2007; Macklin et al., 2010). Contrary to rivers in the eastern USA (e.g. Walter and Merritts, 2008) or in Germany (Houben et al., 2012), there is no evidence that these changes are related to direct human activities in the floodplain such as mill damming, but the floodplain geoecology changes are the indirect result of an intensification of agricultural activities in the catchment.

The abrupt change in floodplain geoecology in Sclage is in contrast to the gradual increase in human impact (Figure 6) at this site. This suggests a time lag between the start of soil erosion and the start of alluvial deposition (e.g. Houben et al., 2012; Lang et al., 2003; Notebaert et al., 2011c), and illustrates that the changes in floodplain geoecology at Sclage are only occurring when a certain threshold has been reached. Quantifying this threshold in terms of area of arable land is, however, still not possible (e.g. Lechterbeck et al., 2009). At Cortil, the increase in human impact is more abrupt, and influences the floodplain geoecology earlier: from c. 2500 cal. BP the increased human impact caused a slight increase in floodplain accumulation rate. However, only after c. 600 cal. BP, when human impact is at its highest level the threshold towards floodplain morphology changes was reached. The differences between the two study sites can be attributed to a stronger connectivity between the cultivated and eroding uplands and floodplains at Cortil compared with the lower degree of connectivity at Sclage. Indeed, in Cortil, the gentle transition from the valley bottom to the low-angle slopes facilitated the continuous exploitation of the entire floodplain–slope catena, whereas in Sclage the steep valley-side slopes remained under forest and thus trapped the majority of sediment that was produced on the more gentle hillslopes higher up (Figure 7). As a result, the threshold conditions between both sites are different.

Conclusions

This study demonstrates that floodplain geoecology (i.e. geomorphology and ecology) of two sites in the upstream part of the Dijle catchment is changing during the middle and late Holocene under the influence of increased human impact in the catchment. Until c. 2500 cal. BP, human impact was nearly absent or localized with no discernible influence on the floodplain geoecology. The river floodplain was relatively stable and consisted of a marshy environment where organic material accumulated. This marshy environment with Alder carr forests and shallow lakes and a multichannel drainage network is suggested to be the natural state of the Dijle catchment headwaters. From c. 2500 cal. BP onwards, human impact gradually increased and forest cover previously dominated by *Tilia* and *Corylus* declined. Our results show that this first increase of human impact on the regional vegetation did not influence the floodplain geoecology dramatically, although the geoecological floodplain response of the two sites is slightly different depending on site-specific geomorphologic (valley slope) and archeological (occupation density) conditions. When anthropogenic land use further intensified after c. 600 cal. BP and sediment delivery crossed a threshold, the floodplain geoecology changed with clearing of the Alder carr forest, the creation of a single channel river and the dominance of minerogenic overbank sedimentation.

The contemporary morphology of the floodplains in the Dijle catchment, with a meandering river bordered by levees and mineral floodplain deposits, has an anthropogenic origin. It contrasts widely with the middle-Holocene floodplains, which were dominated by peat formation in marshes and gyttja deposition in floodplain lakes, and which lack evidence of a well developed main channel. These floodplain geoecological changes are the indirect result of the intensification of cropland activities in the catchment, and comparable changes are also reported for other rivers in temperate west and central Europe (Notebaert and Verstraeten, 2010).

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